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Electrically active defects in as-implanted, deep buried layers in *p*-type silicon

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We have studied electrically active defects in buried layers, produced by heavy ion implantation in silicon, using both conventional deep level transient spectroscopy (DLTS) and an isothermal spectroscopic technique called time analyzed transient spectroscopy operated in constant capacitance mode (CC-TATS). We show that CC-TATS is a more reliable method than DLTS for characterization of the heavily damaged buried layers. The major trap produced in the buried layers in p-type Si by MeV Ar^+ implantation is found to have an energy level at $E_v+0.52$ eV. This trap, believed to be responsible for compensation in the damaged layer, shows exponential capture dynamics. We observed an unusually high thermal activation energy for capture, which is attributed to a macroscopic energy barrier for carriers to reach the buried layer. We observe two other majority carrier traps, and also a minority carrier trap possibly due to inversion within the depletion layer. © *1997 American Institute of Physics.* [S0021-8979(96)06124-5]

I. INTRODUCTION

The suitability of high energy, heavy ion implantation for production of commercially relevant buried layers rests on a thorough understanding of implant-induced defects. Though damage created by heavy ion implantation in semiconductors is being studied extensively[1] at present by many techniques including electron microscopy[2,3] and Rutherford backscattering spectrometry,[4] there are few studies on characterization of electrically active defects.[5,6] Recently, the study of point defects generated by MeV ions in silicon has drawn considerable attention since they seem to play a vital role in structural relaxation of the damaged layer,[7] extended defect formation on annealing,[8] and electrical activation of dopants.[9] Though there have been many studies involving conventional dopant ions such as B, P, As, etc., electrically active defects induced by high energy Ar^+ implantation is less understood, especially in p-type Si. The use of an electrically inactive species such as Ar ion to create the damage helps in separating out effects due purely to implant induced damage from those involving electrical activation of dopants.

However, there are several problems associated with meaningful electrical characterization of deep level defects in as-implanted semiconductors. Principal among them is the effect of a physically disordered region which makes it difficult to obtain interpretable results using standard depletion layer spectroscopies such as deep level transient spectroscopy (DLTS).[10] Large concentration of traps and the presence of series resistance in a diode gives rise to nonexponential transients. Such nonexponentialities in capacitance transient under constant bias can be avoided by performing the transient analysis on the voltage transient in constant capacitance (CC) mode.[11–13] In this method, the capacitance is held constant while carrier emission is monitored by dynamically varying the applied voltage during the transient response through a feedback circuit. The use of isothermal spectroscopic techniques for capacitance and current transients analysis has been explored in the past.[14,15] Time analyzed transient spectroscopy (TATS)[16] is one such isothermal spectroscopic technique where the signal is constructed from difference of values of the transient at two different correlated times. The TATS signal for a voltage transient $V(t)$ is given by[16]

$$S(t)=V(t)-V(t+\gamma t), \tag{1}$$

where γ is an experimentally selectable constant. When plotted against the logarithm of the time, the signal goes through a maximum. Unlike DLTS where the time window is kept fixed and temperature is varied, in this method the time window is varied keeping the temperature constant.

In this work, we studied deep level defects in heavy ion damaged Si using both conventional DLTS and time analyzed transient spectroscopy in the constant capacitance mode (CC-TATS). The presence of a resistive damaged region and high defect densities in the as-implanted material poses severe problems in DLTS characterization. We show that CC-TATS is a more reliable method to characterize electrically active defects in as-implanted Si, and present several interesting results on the most pronounced deep level defect found in buried layers created by MeV implantation.

II. EXPERIMENTAL DETAILS

Polished p-type Czochralski (Cz) Si wafers of 4–7 Ω cm resistivity and (111) orientation were used. Schottky contacts were made using vacuum deposited aluminum. Several control diodes on the same wafer, tested by capacitance versus voltage ($C-V$) measurements, showed a uniform shallow doping concentration of 1.5×10^{15} cm^{-3}. The implantations were performed at room temperature with 1.45 MeV Ar^+ ions for doses of 1 and 5×10^{14} cm^{-2} on the finished device from the front side of the wafer. No postimplantation annealing was done on any of the samples apart from curing the epoxy contact at 70 °C while bonding. A Boonton capacitance meter (model 72B with 50 μs response time) operated

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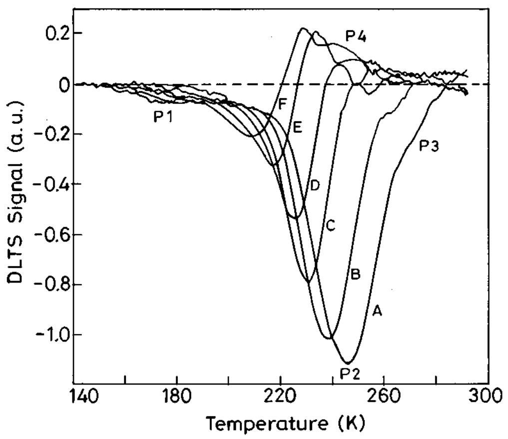

FIG. 1. DLTS spectra of Si irradiated with Ar^+ at dose 1×10^{14} cm^{-2} for rate windows: (A) 500 s^{-1}, (B) 200 s^{-1}, (C) 67 s^{-1}, (D) 33 s^{-1}, (E) 13 s^{-1}, and (F) 5 s^{-1}. The ratio between the two sampling times $t_2/t_1=2$.

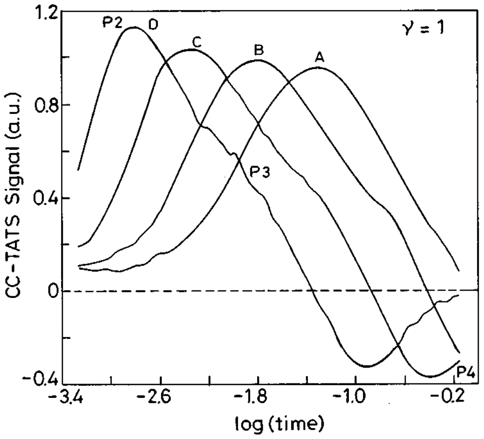

FIG. 2. CC-TATS spectra of the same sample at temperatures: (A) 221 K, (B) 229.4 K, (C) 239.5 K, (D) 250 K. Note the occurrence of two majority carrier peaks (P2, P3) and a minority carrier peak (P4). The filling pulse was applied for 1 s in each case to ensure complete filling of traps.

at 1 MHz was used for all capacitance measurements. The whole setup is computer controlled except for the temperature control.

III. RESULTS AND DISCUSSION

The control sample did not show any trap signature using conventional DLTS up to the detection limit of 10^{-3} of the background doping. Figure 1 shows DLTS spectra for several rate windows for a sample irradiated with a dose of 1×10^{14} cm^{-2} of Ar^+ ions. We list below the major features of our DLTS observations.

(i) The small peak marked P1 in Fig. 1 has an activation energy of 0.37 eV and a capture cross section of 4×10^{-15} cm^2 as estimated from the Arrhenius plot. This peak corresponds to a hole trap commonly attributed to C_iO_i complex[17] in Cz substrates. This level has also been found in unannealed *p*-type Si irradiated with MeV gold ions.[18]

(ii) The line shape of the major peak (marked P2) does not correspond to the standard line shape expected from exponential transients in DLTS. Due to this, it is difficult to obtain its activation energy from an Arrhenius plot. The distortions introduced may be due to several reasons. Since the concentration of traps is expected to be high, the change in capacitance is too large for conventional constant voltage transient to be exponential. It is also known[18] that in case there exists a source of high series resistance in the sample, DLTS peaks shift in temperature and have narrower width. The reduction in peak height for peaks corresponding to lower temperatures, indicate that temperature dependence has a role to play in contributing to nonexponentiality.

(iii) The feature marked P4 in Fig. 1 shows a systematic signal in the positive direction, indicating possible emission from minority carrier traps. Its presence also contributes to line-shape distortion of the major peak P2. However, it is also known that a strong temperature dependence in capture rate and series resistance,[19] if any, can lead to such features in DLTS spectra. There is also a high temperature peak P3, which is not so well resolved in these spectra.

Most of the problems mentioned above regarding nonexponentialities and resulting line-shape distortions can be avoided by using TATS in the constant capacitance mode. Note that TATS, being an isothermal spectroscopy, does not inherit problems regarding temperature dependent sources of distortions of conventional spectroscopies such as DLTS. By using the technique in constant capacitance mode, it is possible to avoid the expected nonexponentialities due to large defect density in constant voltage spectroscopies.[13]

Figure 2 shows CC-TATS spectra for the same sample for several temperatures. In the range of time scales shown in Fig. 2, we see two majority carrier peaks (marked P2, P3) and a minority carrier peak P4.[20] The minority carrier peak appears as a fully developed feature in contrast to DLTS spectra. The peak corresponding to peak P1 in DLTS spectra is too fast to appear for these temperatures. Note that the peak heights are similar for spectra recorded at different temperatures in contrast to DLTS peak heights. Moreover, the line-shape analysis of the major peak (P2) in CC-TATS shows that it results from an exponential transient whereas in both constant voltage DLTS and TATS measurements, it was observed to be broader than expected. This indicates the importance of using constant capacitance mode to study such samples.

Figure 3 shows the Arrhenius plot for the major peak whose emission rates have been obtained from CC-TATS spectra. It gives an activation energy of 0.52 eV with an unusually high capture cross section of 9.9×10^{-14} cm^2.[21] A defect having similar parameters has been observed in heavy ion damaged Si and has been attributed to damage.[22,23] However, such a level is not detected in damage created with light ions. The average concentration (estimated from CC-TATS spectra) of this defect in the buried layer is 3×10^{15} cm^{-3} which is about twice the background doping.[24] For comparison, emission data obtained from DLTS results are also plotted in Fig. 3. Note the nonlinearity in such a plot clearly establishing the superiority of the CC-TATS tech-

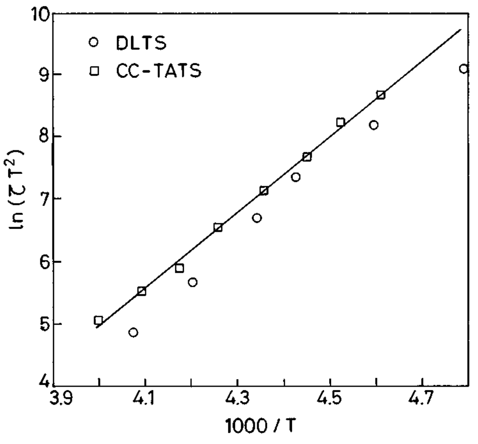

FIG. 3. Arrhenius plot for the major peak (P2) in CC-TATS and DLTS spectra.

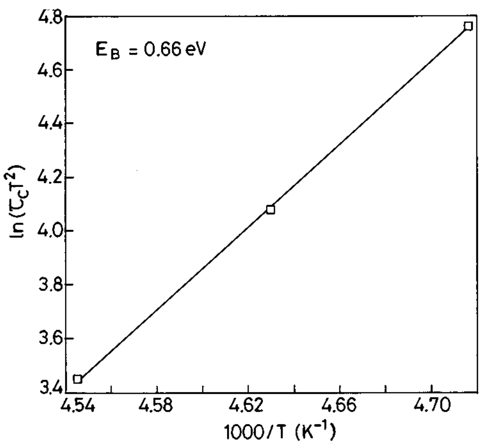

FIG. 5. Arrhenius plot of the capture time constants of the major trap obtained from CC-TATS measurements.

nique. The emission signature obtained from DLTS and TATS[25] is similar to that of a trap reported in B^+ implanted Si.[6]

Figure 4 shows filling time dependence of occupation of the major trap (peak P2) at 216 K determined using constant capacitance varying pulse width technique.[26] Capture is seen to be exponential which is expected from the point defect nature of the traps. However, for the same sample, using constant voltage transients, trap filling during capture is observed to be slow and approximately logarithmic in time. Hence, we conclude that such a slow filling is an artifact of nonexponentiality due to large trap concentration. Similar logarithmic time dependence of capture has been reported from conventional DLTS measurements for plastically deformed silicon with dislocations.[27] Therefore, a conventional DLTS study can mislead one to conclude that the defects are extended defects with time-dependent capture barrier.

Constant capacitance transient measurements using the variable filling pulse width technique at different temperatures reveal strong temperature dependence of capture kinetics of the major trap. Figure 5 shows an Arrhenius plot of capture time constant yielding an activation energy of 0.66 eV, which is unusually high. Since the activation energy for emission is smaller than the observed barrier for capture, it cannot be a microscopic capture barrier associated with the capture cross section of the defect. In fact, since the buried layer always remains within the depletion layer, the observed barrier is due to a limited supply of holes at the buried layer during the filling pulse. Using TRIM simulations,[28] we find that the peak of the damage distribution is located approximately 1.22 μm below the front surface. From the knowledge of zero bias depletion width and the background doping, it is easy to calculate the energy barrier that holes see in trying to reach the damaged layer. It turns out to be approximately equal to the activation energy of capture obtained experimentally.

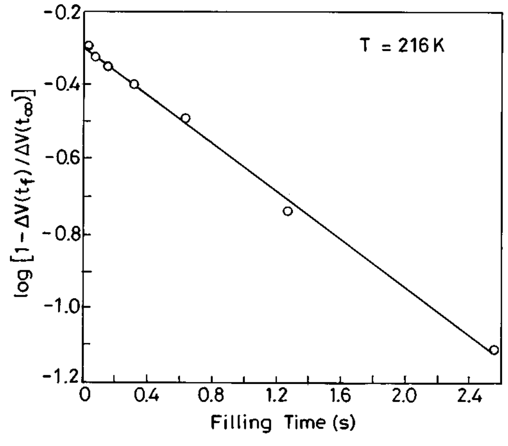

FIG. 4. Filling time dependence of the occupation of observed major trap in as-implanted p-Si using varying pulse width technique in conjunction with CC-TATS.

Occurrence of the negative peak in the CC-TATS spectra cannot be ascribed to the series resistance of the damaged layer created by Ar^+ ions since a high dc resistance does not distort transients in the CC mode of operation. However, this peak seems to be characteristic of p-Si samples irradiated with heavy ions. Similar studies on n-Si did not show this negative peak.[18] We ascribe this negative peak to changes in occupancy of minority carrier traps due to presence of inversion layer caused by band bending in the damaged region. A simple calculation of band bending at zero bias shows that the interface at the damaged region would be inverted. This seems to indicate that a minority carrier trap can indeed be filled within depletion layer.

IV. CONCLUSION

In summary, CC-TATS has been used to characterize deep buried layer in MeV Ar^+ implanted p-Si. Its advantages over conventional DLTS measurements are demonstrated. As-implanted samples show three majority carrier related peaks of which the major peak corresponds to a midgap energy level which is probably the main source of compensation of carriers in the damaged layer. From varying filling pulse width measurements, capture is seen to be temperature activated and the barrier is associated with macroscopic band bending.

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